

# Stefano Gariazzo

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## Neutrino clustering in the Milky Way

*Based on arxiv:1706[6/7].[0-9]{5}*

*In collaboration with P. F. de Salas,  
J. Lesgourgues, S. Pastor*

- 1 Cosmic neutrino background and neutrino clustering
  - Neutrinos in the early universe
  - PTOLEMY
  - Neutrino clustering
- 2 Matter distributions in the Milky Way
  - Dark Matter
  - Baryons
- 3 The local neutrino overdensity
  - Results for (nearly) minimal neutrino masses
  - Results for non-minimal neutrino masses: 150 meV
- 4 Conclusions

## 1 Cosmic neutrino background and neutrino clustering

- Neutrinos in the early universe
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## 2 Matter distributions in the Milky Way

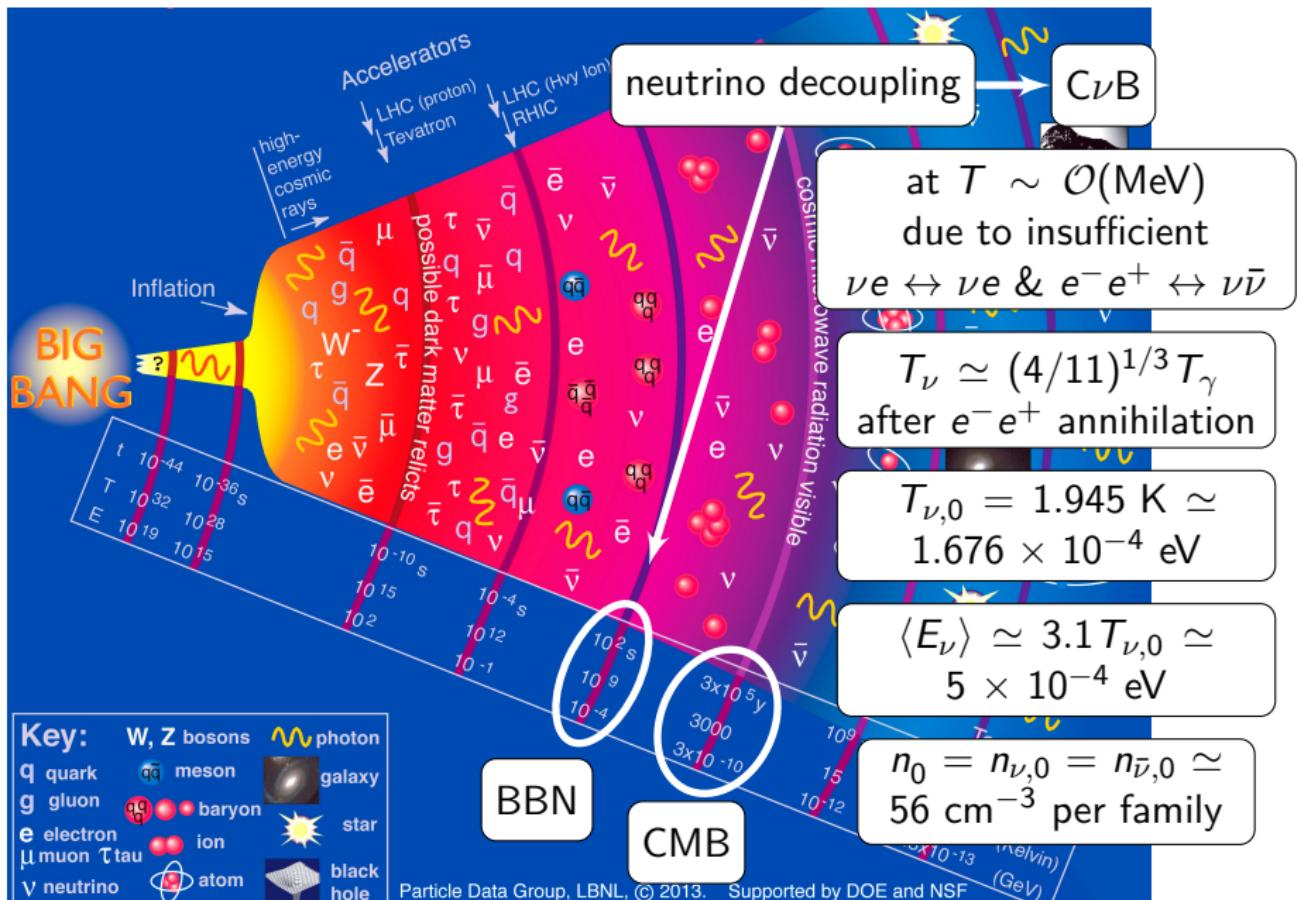
- Dark Matter
- Baryons

## 3 The local neutrino overdensity

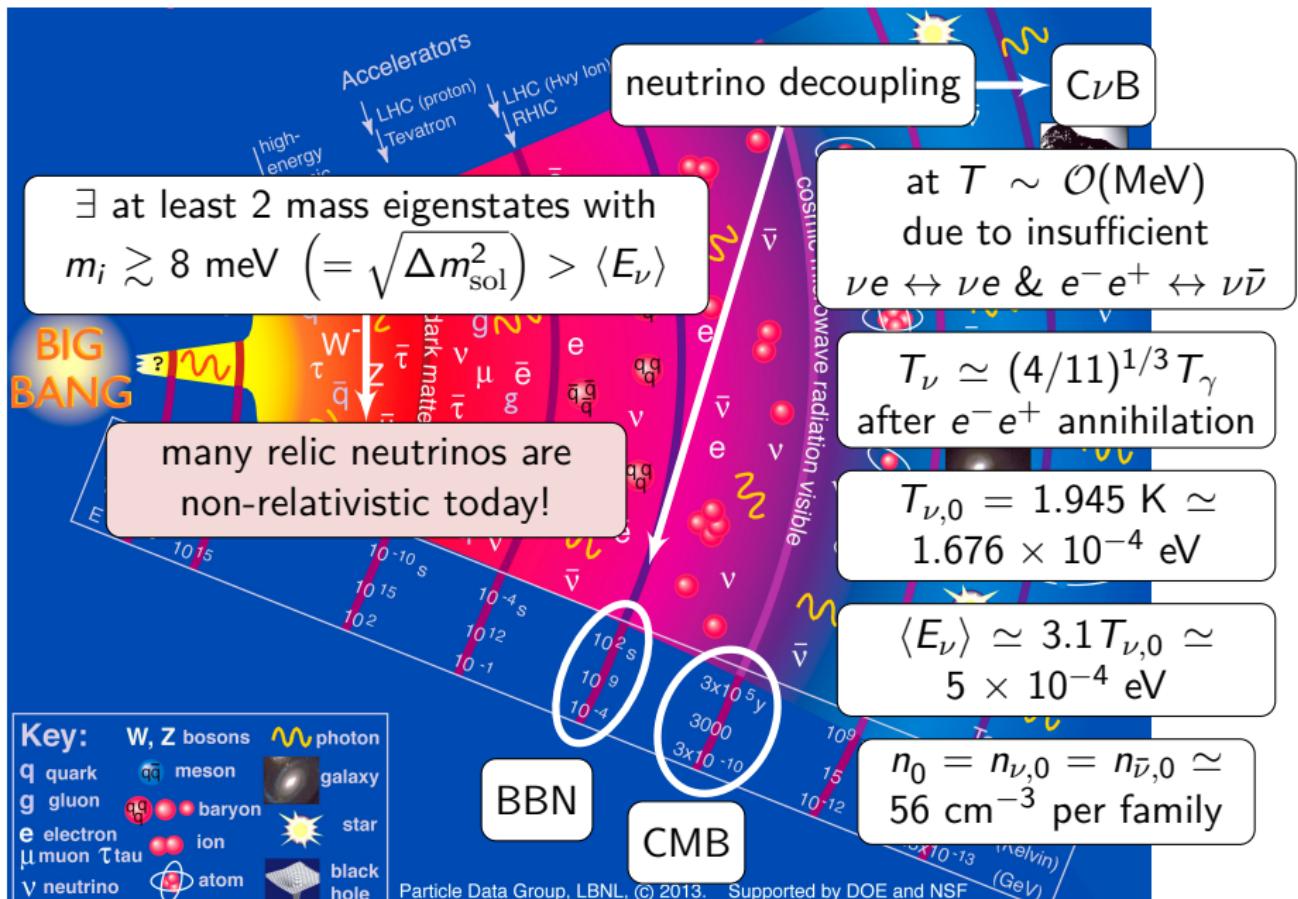
- Results for (nearly) minimal neutrino masses
- Results for non-minimal neutrino masses: 150 meV

## 4 Conclusions

# History of the universe



# History of the universe



## Dirac neutrinos

active:	sterile:
$\nu_L, n(\nu_L) = n_0$	$\nu_R, n(\nu_R) \simeq 0$
$\bar{\nu}_R, n(\bar{\nu}_R) = n_0$	$\bar{\nu}_L, n(\bar{\nu}_L) \simeq 0$

total:  $n_{C\nu B} \simeq 6n_0$

## Majorana neutrinos

active:	sterile:
$\nu_L, n(\nu_L) = n_0$	$N_L, n(N_L) = 0$
$\nu_R, n(\nu_R) = n_0$	$N_R, n(N_R) = 0$

total:  $n_{C\nu B} \simeq 6n_0$

NOTE: free-streaming conserves helicity, not chirality!

because neutrinos are massive and become non-relativistic during expansion

$n(\nu_{h_L}) = n_0$	$n(\nu_{h_R}) \simeq 0$
$n(\bar{\nu}_{h_R}) = n_0$	$n(\bar{\nu}_{h_L}) \simeq 0$

only left-helical!

$n(\nu_{h_L}) = n_0$	$n(N_{h_L}) = 0$
$n(\nu_{h_R}) = n_0$	$n(N_{h_R}) = 0$

both left and right-helical

if not completely free-streaming, helicities can be flipped

$\Rightarrow$  mix of helicities:  $n(\nu_{h_L}) = n(\bar{\nu}_{h_R}) = n(\nu_{h_R}) = n(\bar{\nu}_{h_L}) = n_0/2$

no change for Majorana

## Relic neutrinos in cosmology: $N_{\text{eff}}$

Radiation energy density  $\rho_r$  in the early Universe:

$$\rho_r = \left[ 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_\gamma = [1 + 0.2271 N_{\text{eff}}] \rho_\gamma$$

$\rho_\gamma$  photon energy density,  $7/8$  is for fermions,  $(4/11)^{4/3}$  due to photon reheating after neutrino decoupling

- $N_{\text{eff}} \rightarrow$  all the radiation contribution not given by photons
- $N_{\text{eff}} \simeq 1$  correspond to a single family of active neutrino, in equilibrium in the early Universe
- Active neutrinos:  
 $N_{\text{eff}} = 3.046$  [Mangano et al., 2005] (damping factors approximations) ~  
 $N_{\text{eff}} = 3.045$  [de Salas et al., 2016] (full collision terms)  
due to not instantaneous decoupling for the neutrinos
- + Non Standard Interactions:  $3.040 < N_{\text{eff}} < 3.059$  [de Salas et al., 2016]

Observations:  $N_{\text{eff}} \simeq 3.04 \pm 0.2$  [Planck 2015]

Indirect probe of cosmic neutrino background!

At least two  $C\nu B$  neutrinos over three are non-relativistic now!

How to detect non-relativistic neutrinos?

a process without energy threshold is necessary

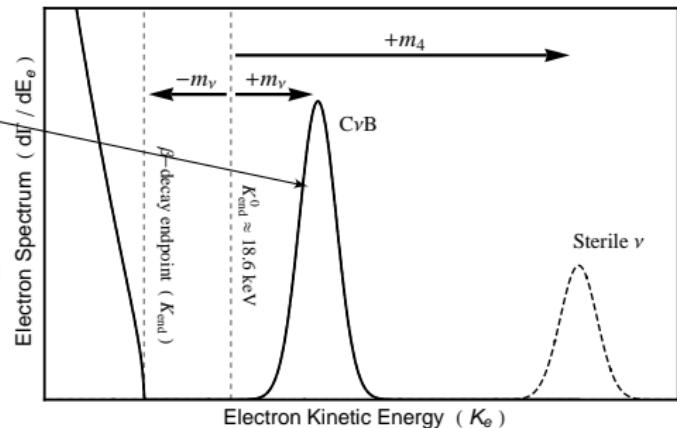
[Weinberg, 1962]: neutrino capture in  $\beta$ -decaying nuclei  $\nu + n \rightarrow p + e^-$

signal is a peak at  $2m_\nu$  above  $\beta$ -decay endpoint

only with a lot of material

need a very good energy resolution

Good candidate: tritium



(low  $Q$ -value) + (good availability of  ${}^3\text{H}$ ) +  $(\text{high cross section of } \nu + {}^3\text{H} \rightarrow {}^3\text{He} + e^-)$

Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

expected resolution  $\Delta \simeq 0.1$  eV

built only for  $C\nu B$

$M_T = 100$  g atomic tritium

can probe  $m_\nu \simeq 1.4\Delta \simeq 0.14$  eV

(must distinguish  $C\nu B$  events from  $\beta$ -decay ones)

$$\Gamma_{C\nu B} = \sum_{i=1}^3 |U_{ei}|^2 [n_i(\nu_{h_R}) + n_i(\nu_{h_L})] N_T \bar{\sigma}$$

$N_T$  number of  ${}^3H$  nuclei in a sample of mass  $M_T$        $\bar{\sigma} = \simeq 3.834 \times 10^{-45} \text{ cm}^2$        $n_i$  number density of neutrino  $i$

$$\Gamma_{C\nu B}^D = \sum_{i=1}^3 |U_{ei}|^2 \left[ 2 \left( \frac{n_0}{2} \right) \right] N_T \bar{\sigma} \simeq 4 \text{ yr}^{-1}$$

Dirac:                          (without clustering)                          Majorana:

$$\Gamma_{C\nu B}^M = \sum_{i=1}^3 |U_{ei}|^2 [2(n_0)] N_T \bar{\sigma} \simeq 8 \text{ yr}^{-1}$$

$$\Gamma_{C\nu B}^M = 2\Gamma_{C\nu B}^D$$

### Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

expected resolution  $\Delta \simeq 0.1$  eV

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enhancement from  $\nu$  clustering in the galaxy?

$$\Gamma_{C\nu B} = \sum_{i=1}^3 |U_{ei}|^2 [n_i(\nu_{h_R}) + n_i(\nu_{h_L})] N_T \bar{\sigma}$$

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## $\nu$ clustering with N-one-body simulations

[arxiv:170(6|7).[0-9]{5}]

Milky Way (MW) matter attracts neutrinos!

clustering → 
$$\Gamma_{C\nu B} = \sum_{i=1}^3 |U_{ei}|^2 f_c(m_i) [n_{i,0}(\nu_{h_R}) + n_{i,0}(\nu_{h_L})] N_T \bar{\sigma}$$

$f_c(m_i)$  clustering factor → How to compute it?

Idea from [Ringwald & Wong, 2004] → **N-one-body** =  $N \times$  single  $\nu$  simulations

→ each  $\nu$  evolved from initial conditions at  $z = 3$

→ spherical symmetry, coordinates  $(r, \theta, p_r, l)$

→ need  $\rho_{\text{matter}}(z) = \rho_{\text{DM}}(z) + \rho_{\text{baryon}}(z)$

Assumptions:

$\nu$ s are independent

only gravitational interactions

$\nu$ s do not influence matter evolution

$(\rho_\nu \ll \rho_{\text{DM}})$

how many  $\nu$ s is "N"?

→ must sample all possible  $r, p_r, l$

→ must include all possible  $\nu$ s that reach the MW  
(fastest ones may come from  
several (up to  $\mathcal{O}(100)$ ) Mpc!)

given  $N \nu$ :

→ weigh each neutrinos

→ reconstruct final density profile with kernel method from [Merritt & Tremblay, 1994]

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# Dark matter: profiles today

NFW profile:

$$\mathcal{N}_{\text{NFW}} \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{-3+\gamma} = \rho_{\text{DM}}(r) = \mathcal{N}_{\text{Ein}} \exp\left\{-\frac{2}{\alpha} \left(\left(\frac{r}{r_s}\right)^\alpha - 1\right)\right\}$$

$$\mathcal{N}_{\text{NFW}} = 2^{3-\gamma} \rho_{\text{NFW}}(r_s)$$

normalization

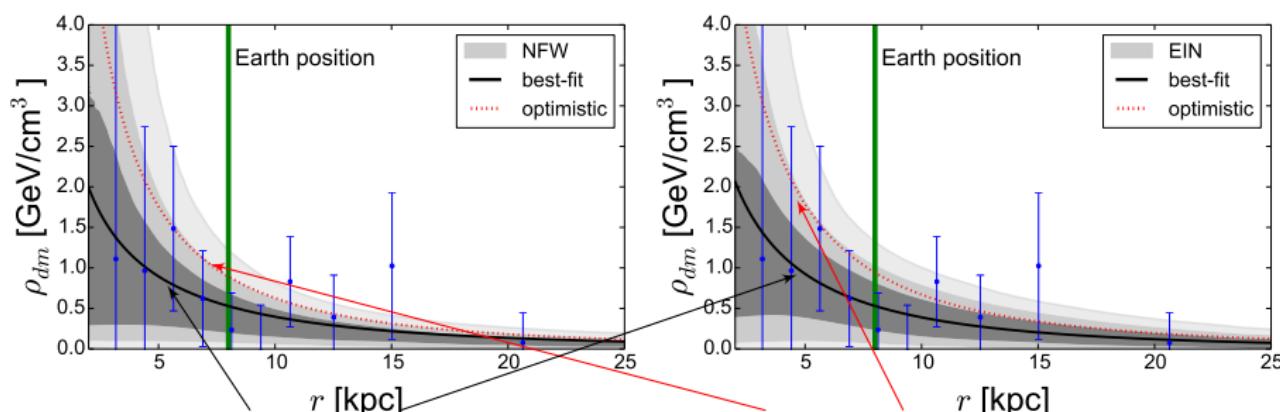
$$\mathcal{N}_{\text{NFW}}, r_s, \gamma$$

parameters

Einasto (EIN) profile:

$$\mathcal{N}_{\text{Ein}} = \rho_{\text{Ein}}(r_s)$$

$$\mathcal{N}_{\text{Ein}}, r_s, \alpha$$



**Best-fit** profiles

fit of **data points** from [Pato & Iocco, 2015]

**optimistic:** close to  $2\sigma$  upper limits

# DM: Time evolution of the profiles

[arxiv:170(6|7).[0-9]{5}]

profile evolution from universe expansion

$$\left\{ \begin{array}{l} \rho_{\text{cr}}(z) = \frac{3}{8\pi G} H^2(z) \\ F_{\text{cr}}(z) = \Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0} \\ H^2(z) = H_0^2 F_{\text{cr}}(z) \\ \rho_{\text{cr}}(z) = F_{\text{cr}}(z) \times \rho_{\text{cr}}(z=0) \end{array} \right.$$

$$M_{\text{vir}} = \frac{4\pi}{3} \Delta_{\text{vir}}(z) \rho_{\text{cr}}(z) a^3 r_{\text{vir}}^3(z)$$

constant in time

virial radius  $r_{\text{vir}}$

radius of sphere containing  $M_{\text{vir}}$ ,  
average density  $\Delta_{\text{vir}}(z) \times \rho_{\text{cr}}(z)$

but  $\rho_{\text{DM}} = \rho_{\text{DM}}(r; r_s, \mathcal{N}, [\gamma|\alpha])$

relation between  $r_s$  and  $r_{\text{vir}}$ ?



from N-body [Dutton et al., 2014]

$$r_{\text{vir}}(M_{\text{vir}}, z) = \left( \frac{3M_{\text{vir}}}{4\pi\rho_{\text{cr},0}\Omega_{m,0}} \right)^{1/3} \left( \frac{\Omega_m(z)}{\Delta_{\text{vir}}(z)F_{\text{cr}}(z)} \right)^{1/3}$$

$$\Delta_{\text{vir}}(z) = \begin{cases} 200 & \text{for EIN,} \\ 18\pi^2 + 82\lambda(z) - 39\lambda(z)^2 & \text{for NFW.} \end{cases}$$

$$\lambda(z) = \Omega_m(z) - 1$$

final expression  $\Rightarrow \rho_{\text{DM}}(r, z) = \mathcal{N}(z) \tilde{\rho}_{\text{DM}}(r, r_s(z))$

$\tilde{\rho}_{\text{DM}}$  depends on redshift  
only through  $r_s$

$a = 1/(1+z)$ ,  $h = H_0/(100 \text{ Km s}^{-1} \text{ Mpc}^{-1})$  –  $h = 0.6727$ ,  $\Omega_{m,0} = 0.3156$ ,  $\Omega_{\Lambda,0} = 0.6844$  [Planck Collaboration, 2015]

# Baryons: the complexity of a structure

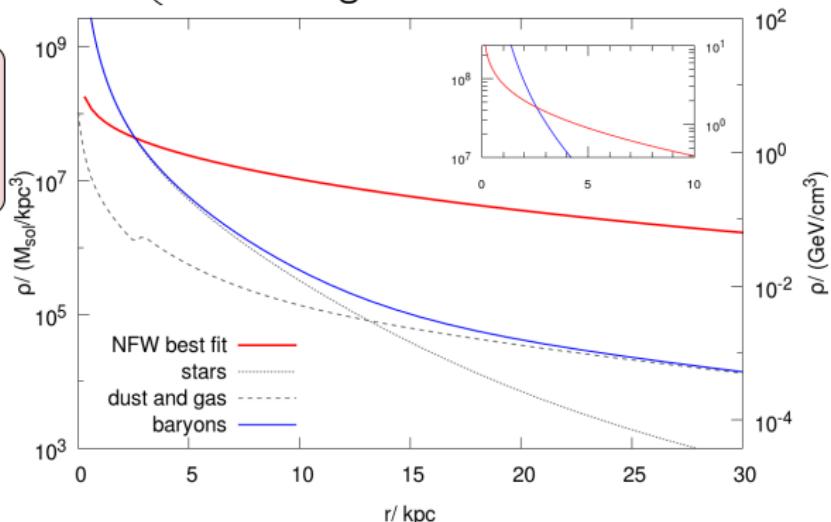
Complex problem: how to model baryon content of a galaxy?

e.g. [Pato et al., 2015]:  
70 different baryonic models

{ 7 models for the bulge  
x  
5 for the disc  
x  
2 for the gas

[Misiriotis et al., 2006]:  
5 independent components

{ warm dust  
cold dust  
stars  
atomic  $H$  gas  
molecular  $H$  gas



our case: [Misiriotis et al., 2006], spherically symmetrized

# Baryons: redshift evolution

baryon evolution with redshift?

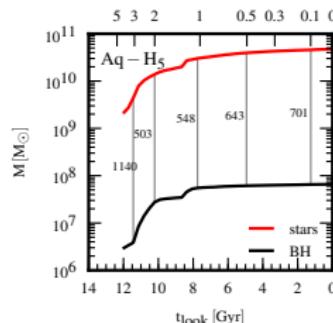
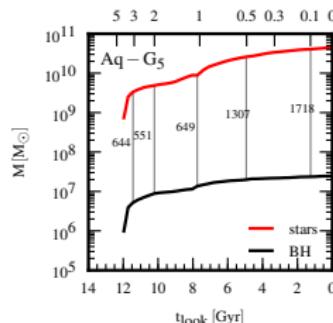
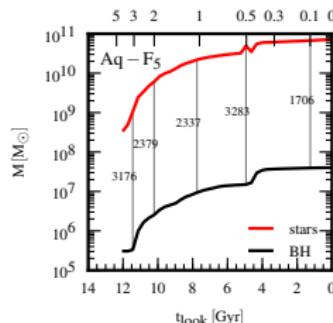
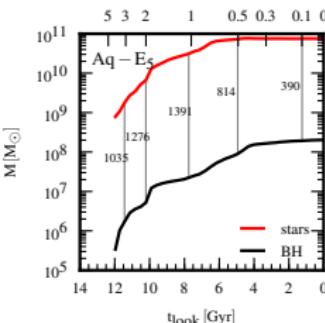
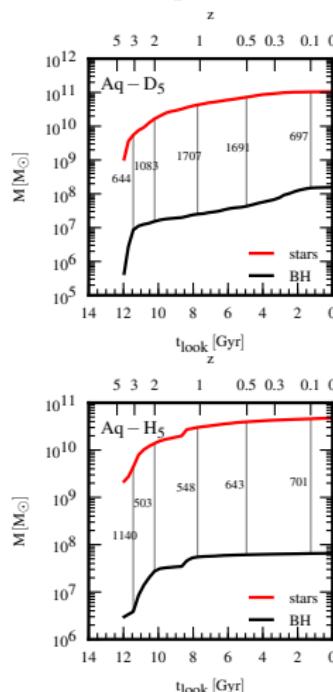
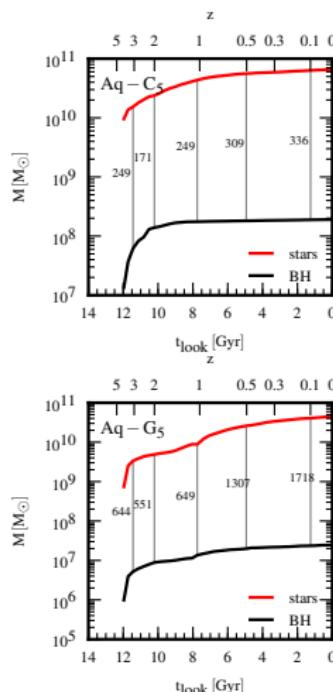
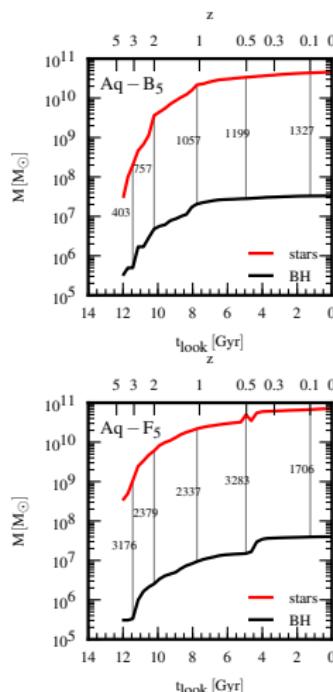
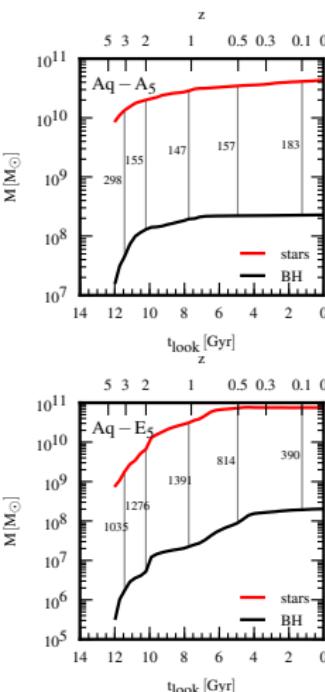
from [Marinacci et al., 2013]

results of full N-body simulations

$\mathcal{N}_{\text{bar}}(z)$  from  $M(z)$

mean of 8 simulations

based on Aquarius simulation:  $M_{\text{Aq}} \simeq M_{\text{MW}}$



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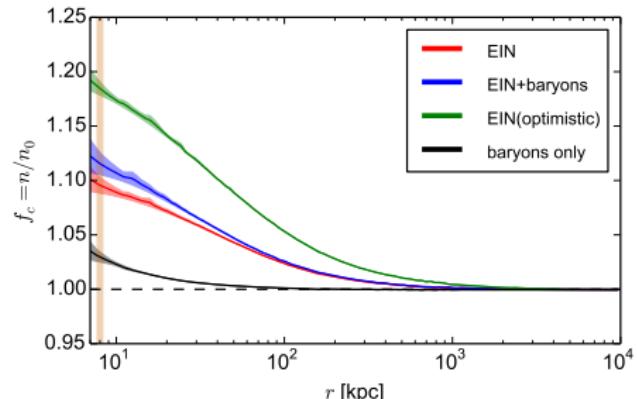
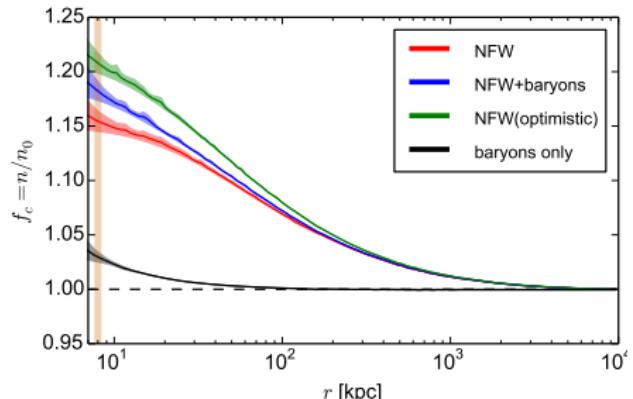
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- Results for (nearly) minimal neutrino masses
- Results for non-minimal neutrino masses: 150 meV

## 4 Conclusions

# Overdensity when $m_{\text{heaviest}} \simeq 60 \text{ meV}$

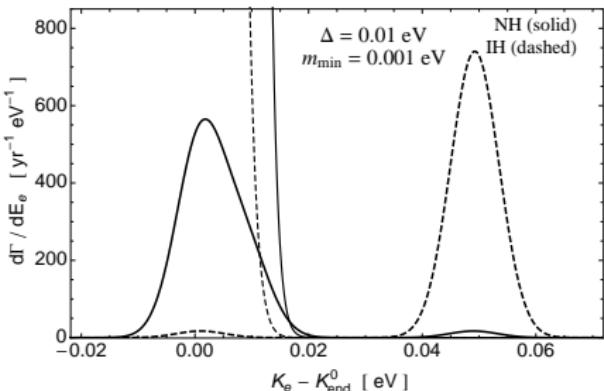
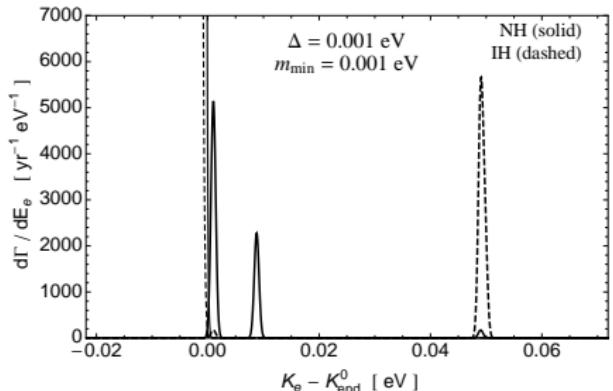
[arxiv:1706(7).0-9]{5}]



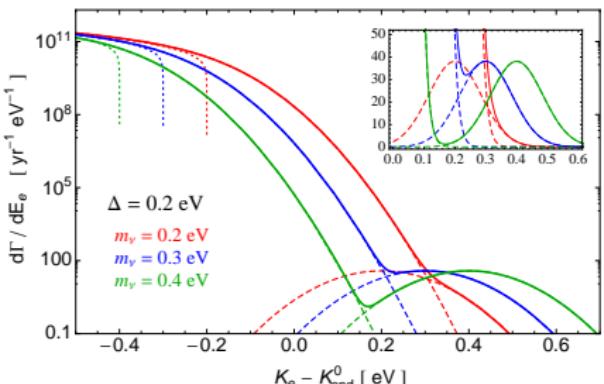
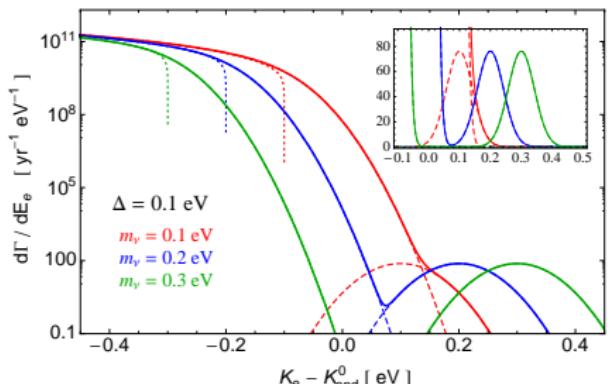
masses	ordering	matter halo	overdensity $f_c$ $f_1 \simeq f_2$	$f_3$	$\Gamma_{\text{tot}}^D (\text{yr}^{-1})$	$\Gamma_{\text{tot}}^M (\text{yr}^{-1})$
any	any	any	no clustering		4.06	8.12
$m_3 = 60 \text{ meV}$	NO	NFW(+bar)	$\sim 1$	1.15 (1.18)	4.07 (4.08)	8.15 (8.15)
		NFW optimistic		1.21	4.08	8.16
		EIN(+bar)		1.09 (1.12)	4.07 (4.07)	8.14 (8.14)
		EIN optimistic		1.18	4.08	8.15
$m_1 \simeq m_2 = 60 \text{ meV}$	IO	NFW(+bar)	$\sim 1$	1.15 (1.18)	4.66 (4.78)	9.31 (9.55)
		NFW optimistic		1.21	4.89	9.77
		EIN(+bar)		1.09 (1.12)	4.42 (4.54)	8.84 (9.07)
		EIN optimistic		1.18	4.78	9.55

ordering dependence from  $\Gamma_{C\nu B} = \sum_{i=1}^3 |U_{ei}|^2 f_i [n_i(\nu_{hR}) + n_i(\nu_{hL})] N_T \bar{\sigma}$

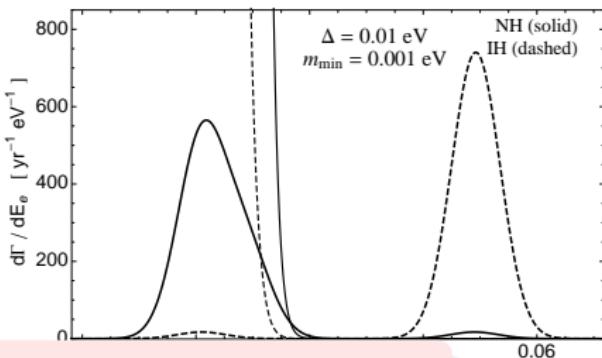
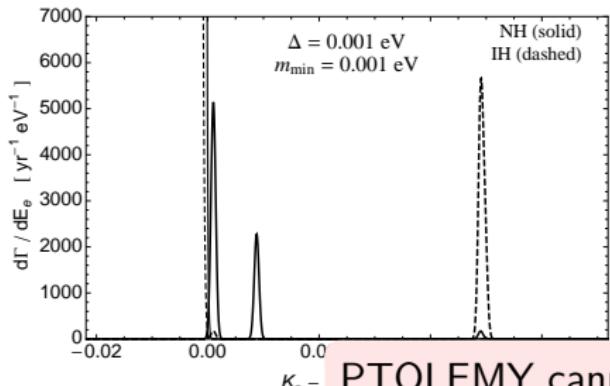
Hierarchical:



Degenerate: (solid: measured, dotted: ideal with  $\Delta = 0$ )

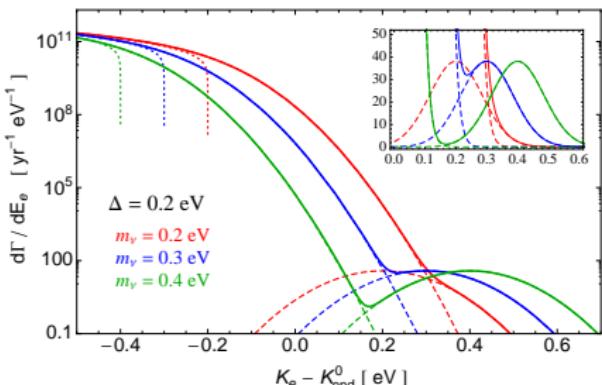
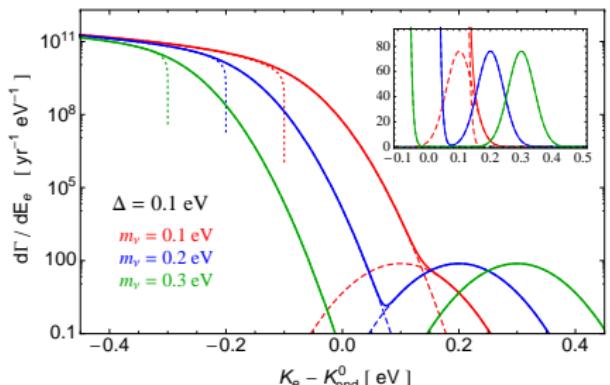


Hierarchical:



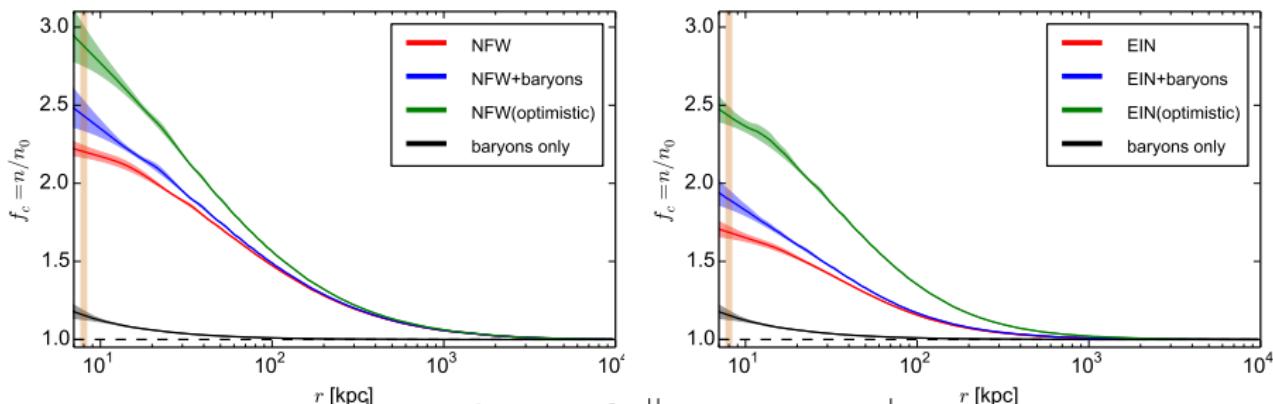
PTOLEMY cannot detect  $m_{\nu} \lesssim 0.15 \text{ eV}!$

Degenerate: (solid: measured, dotted: ideal with  $\Delta = 0$ )



# Overdensity when $m_\nu \simeq 150$ meV

$\implies$  minimal mass detectable by PTOLEMY if  $\Delta \simeq 100\text{--}150$  meV



matter halo	overdensity $f_c$ $f_1 \simeq f_2 \simeq f_3$	$\Gamma_{\text{tot}}^D (\text{yr}^{-1})$	$\Gamma_{\text{tot}}^M (\text{yr}^{-1})$
any	no clustering	4.06	8.12
NFW(+bar)	2.18 (2.44)	8.8 (9.9)	17.7 (19.8)
NFW optimistic	2.88	11.7	23.4
EIN(+bar)	1.68 (1.87)	6.8 (7.6)	13.6 (15.1)
EIN optimistic	2.43	9.9	19.7

no ordering dependence:  $m_1 \simeq m_2 \simeq m_3 \implies f_1 \simeq f_2 \simeq f_3$

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## Conclusions

- Cosmic Neutrino Background ( $C\nu B$ ) predicted but not detected:
  - only  $N_{\text{eff}} \simeq 3.04$  as indirect probe
  - must detect scattering of *non-relativistic* neutrinos!
- massive  $\nu$  can **cluster** in the local matter distribution
  - $N$ -one-body method: follow  $N$  single neutrinos in the Milky Way
  - requires knowledge of matter (DM, baryons) profiles and their evolution
- to **detect** relic neutrinos:
  - process without threshold required
    - $\nu$  capture on  $\beta$ -decaying nuclei
    - PTOLEMY proposal with 100g of tritium
  - **very good energy resolution  $\Delta$**  is necessary to probe  $m_\nu \gtrsim 1.4\Delta$
- for *non-minimal*  $\nu$  masses, PTOLEMY can:
  - detect relic neutrinos (for the first time ✓)
  - study non-relativistic neutrinos (for the first time ✓)
  - probe the neutrino clustering (for the first time ✓)
    - constrain the matter profile of our galaxy
  - measure the absolute neutrino masses (for the first time ?)
  - test Dirac/Majorana nature (for the first time ?)
- and also detect relic sterile neutrinos (if any ?)

5

Backup slides

## Equations for the neutrino clustering

Lagrangian for a neutrino ( $m_\nu$ ) in a gravitational potential well  $\phi(\mathbf{x}, \tau)$ :

$$L(r, \theta, \dot{r}, \dot{\theta}, \tau) = \frac{a}{2} m_\nu (\dot{r}^2 + r^2 \dot{\theta}^2 - 2\phi(r, \tau))$$

Hamiltonian:  $H(r, \theta, p_r, l, \tau) = \frac{1}{2am_\nu} \left( p_r^2 + \frac{l^2}{r^2} \right) + am_\nu \phi(r, \tau)$

Canonical momenta:  $p_r = \frac{\partial L}{\partial \dot{r}} = am_\nu \dot{r}$ ,  $l = rp_\theta = \frac{\partial L}{\partial \dot{\theta}} = am_\nu r^2 \dot{\theta}$

Hamilton equations:

$$\begin{aligned} \frac{\partial H}{\partial p_r} &= \frac{dr}{d\tau} = \frac{p_r}{am_\nu} & \frac{\partial H}{\partial l} &= \frac{d\theta}{d\tau} = \frac{l}{am_\nu r^2} \\ -\frac{\partial H}{\partial r} &= \frac{dp_r}{d\tau} = \frac{l^2}{am_\nu r^3} - am_\nu \frac{\partial \phi}{\partial r} & -\frac{\partial H}{\partial \theta} &= \frac{dl}{d\tau} = 0 \end{aligned}$$

Gravitational potential:  $\phi(r, \tau)$

Known from the Poisson equation  $\nabla^2 \phi = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial \phi}{\partial r} \right) = 4\pi G a^2 \rho_{\text{matter}}(r, \tau)$

$$\frac{\partial \phi}{\partial r} = \frac{G}{ar^2} M_{\text{matter}}(r, \tau), \quad M_{\text{matter}}(r, \tau) = 4\pi a^3 \int_0^r \rho_{\text{matter}}(r', \tau) r'^2 dr'$$

## Reconstruction of $n(r)$ from N-one-body neutrinos

[Merritt et al., 1994]

[Ringwald et al., 2004] sample neutrino  $i$  starts in  $(r, p_r, p_T)$

each  $\nu$  is representative of a bin between  $(r_a, p_{r,a}, p_{T,a})$  and  $(r_b, p_{r,b}, p_{T,b})$

$$\rightarrow \text{weight of the neutrino } i: w_i = \int_{(r, p_r, p_T)_a}^{(r, p_r, p_T)_b} \int_{\theta, \phi, \varphi} dN =$$

$$w_i = 8\pi^2 T_{\nu,0}^3 \int_{r_a}^{r_b} r^2 dr \int_{y_a}^{y_b} f(y) y^2 dy \int_{\psi_a}^{\psi_b} \sin \psi d\psi$$

$$y = p/T_{\nu,0}$$

$f(y)$  Fermi-Dirac

How to reconstruct the number density?

$\nu_i$  smeared around the surface of a sphere with radius  $r_i$  centered in  $r = 0$ ,

$$\text{gaussian kernel: } K(r, r_i, h) = \frac{1}{2(2\pi)^{3/2}} \frac{h^2}{r \cdot r_i} \left[ e^{-(r-r_i)^2/2h^2} - e^{-(r+r_i)^2/2h^2} \right]$$

$$n(r) = \sum_{i=1}^N \frac{w_i}{h^3} K(r, r_i, h)$$

$h$  window width

## Additional clustering due to other galaxies

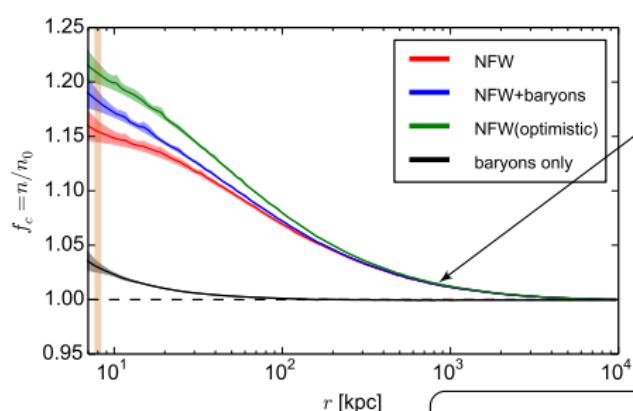
nearest galaxies: various MW satellites

with  $M_{\text{sat}} \ll M_{\text{MW}}$  → negligibly small  $\nu$  halo

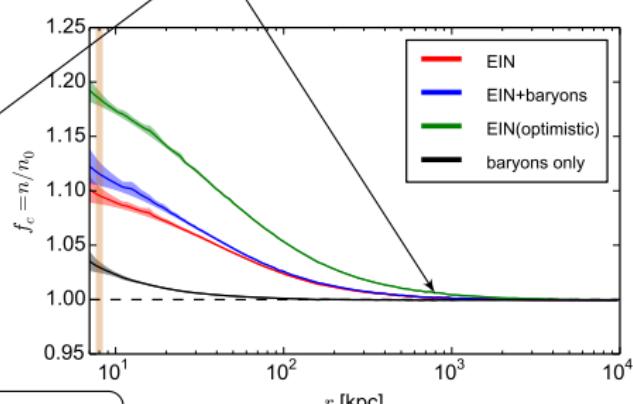
nearest big galaxy:

Andromeda →  $f_c$  increased of  $\lesssim 0.03$

$$M_{\text{Andromeda}} = M_{\text{MW}} \times \mathcal{O}(1) - d_{\text{Andromeda}} \simeq 800 \text{ kpc}$$



$$m_{\text{heaviest}} \simeq 60 \text{ meV}$$



(halo is less diffuse for higher  $\nu$  masses)

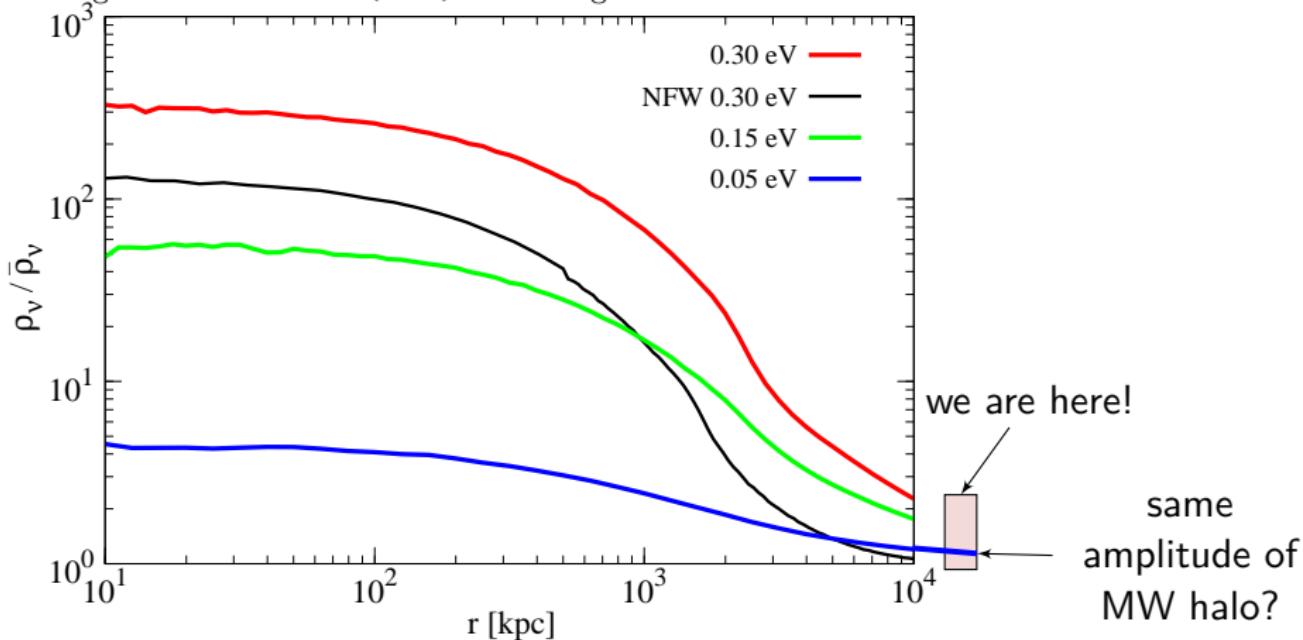
## Additional clustering due to Virgo cluster

nearest galaxy cluster:

Virgo cluster

very wide  $\nu$  halo, may reach Earth

$$M_{\text{Virgo}} = M_{\text{MW}} \times \mathcal{O}(10^3) — d_{\text{Virgo}} \simeq 16 \text{ Mpc}$$



[Villaescusa-Navarro et al., JCAP 1106 (2011) 027]

## Short Baseline (SBL) anomaly

[SG et al., JPG 43 (2016) 033001]

Problem: **anomalies** in SBL experiments  $\Rightarrow \begin{cases} \text{errors in flux calculations?} \\ \text{deviations from } 3\nu \text{ description?} \end{cases}$

A short review:

**LSND** search for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ , with  $L/E = 0.4 \div 1.5 \text{ m/MeV}$ . Observed a  $3.8\sigma$  excess of  $\bar{\nu}_e$  events [Aguilar et al., 2001]

**Reactor** re-evaluation of the expected anti-neutrino flux  $\Rightarrow$  disappearance of  $\bar{\nu}_e$  events compared to predictions ( $\sim 3\sigma$ ) with  $L < 100 \text{ m}$  [Azabajan et al., 2012]

**Gallium** calibration of GALLEX and SAGE Gallium solar neutrino experiments give a  $2.7\sigma$  anomaly (disappearance of  $\nu_e$ ) [Giunti, Laveder, 2011]

**MiniBooNE** (**inconclusive**) search for  $\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ , with  $L/E = 0.2 \div 2.6 \text{ m/MeV}$ . No  $\nu_e$  excess detected, but  $\bar{\nu}_e$  excess observed at  $2.8\sigma$  [MiniBooNE Collaboration, 2013]

Possible explanation:

Additional squared mass difference  
 $\Delta m_{\text{SBL}}^2 \simeq 1 \text{ eV}^2$

See also  
[SG et al., 2017]

## 3+1 Neutrino Model

new  $\Delta m_{\text{SBL}}^2 \Rightarrow 4$  neutrinos!



$\nu_4$  with  $m_4 \simeq 1$  eV,  
no weak interactions



light sterile neutrino (LS $\nu$ )

3 (active) + 1 (sterile) mixing:

$$\nu_\alpha = \sum_{k=1}^{3+1} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau, s)$$

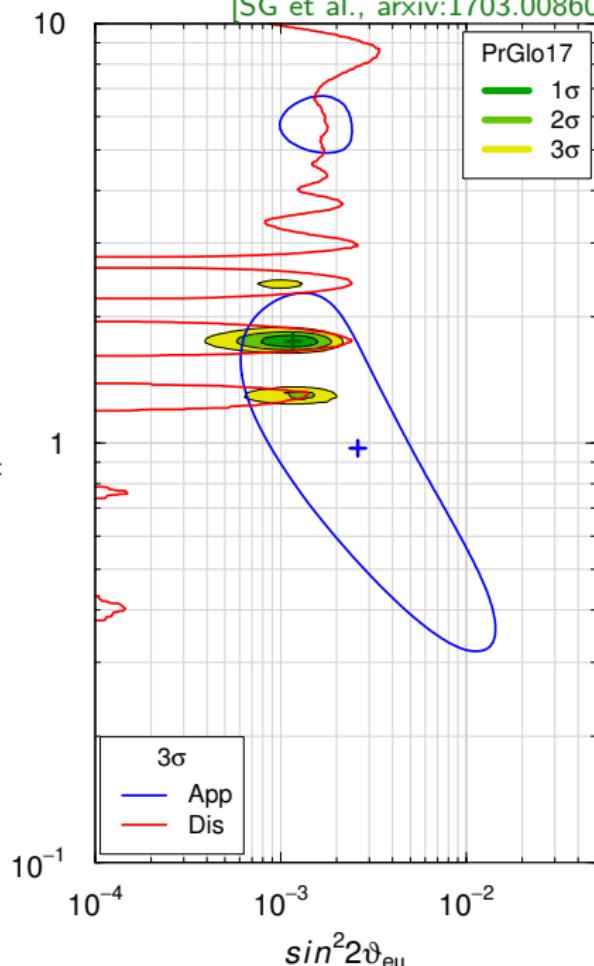
$\nu_s$  is mainly  $\nu_4$ :

$$m_s \simeq m_4 \simeq \sqrt{\Delta m_{41}^2} \simeq \sqrt{\Delta m_{\text{SBL}}^2}$$

assuming  $m_4 \gg m_i$  ( $i = 1, 2, 3$ )

can  $\nu_4$  thermalize in the early  
Universe through oscillations?

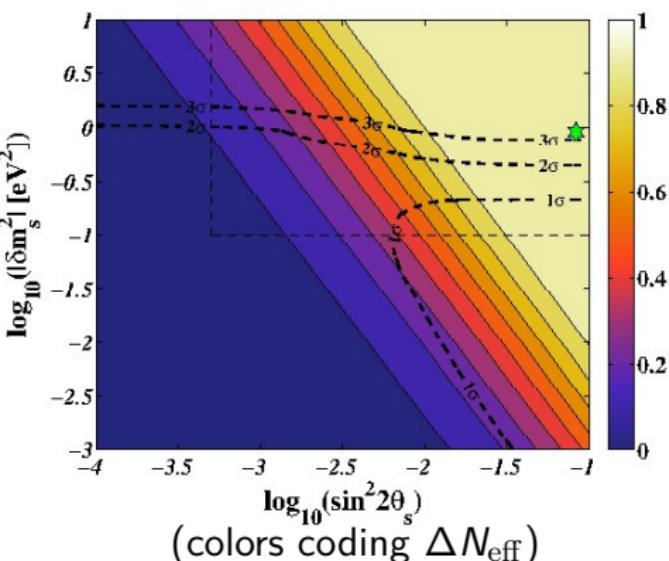
[SG et al., arxiv:1703.00860]



# LS $\nu$ thermalization

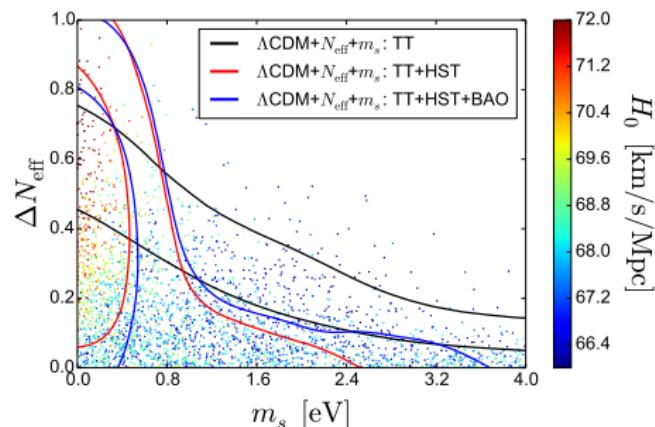
Using SBL best-fit parameters for the LS $\nu$  ( $\Delta m_{41}^2$ ,  $\theta_s$ ):

[Hannestad et al., JCAP 1207 (2012) 025]



[Archidiacono, SG et al., JCAP 08 (2016) 067]

but cosmological fits give:



$\Delta N_{\text{eff}}$  should be  $\simeq 1$ , but it is disfavoured! (new physics?)

[to be precise:  $\Delta N_{\text{eff}}$  is slightly smaller at CMB decoupling, when the LS $\nu$  starts to be non-relativistic]

## Assumptions and useful equations

[arxiv:170(6|7).[0-9]{5}]

We assume possible incomplete thermalization

(due to some unknown new physics)

$$f_4(p) = \frac{\Delta N_{\text{eff}}}{e^{p/T_\nu} + 1} = \Delta N_{\text{eff}} f_{\text{active}}(p)$$

$$\Delta N_{\text{eff}} = \left[ \frac{1}{\pi^2} \int dp p^3 f_4(p) \right] / \left[ \frac{7}{8} \frac{\pi^2}{15} T_\nu^4 \right]$$

$$\bar{n}_4 = \frac{g_4}{(2\pi)^3} \int f_4(p) p^2 dp = n_0 \Delta N_{\text{eff}}$$

$$n_4 = n_0 f_c(m_4) \Delta N_{\text{eff}}$$

( $f_c(m_4)$  is independent of  $\Delta N_{\text{eff}}$ )

$$\Gamma_4^{M(D)} \simeq \Delta N_{\text{eff}} |U_{e4}|^2 f_c(m_4) \Gamma_{\text{C}\nu\text{B}}^{M(D)}$$

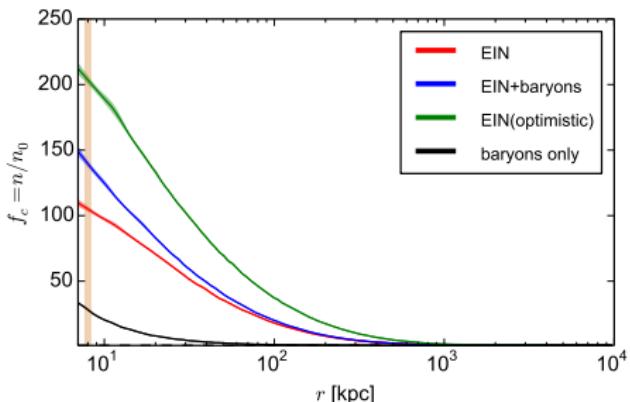
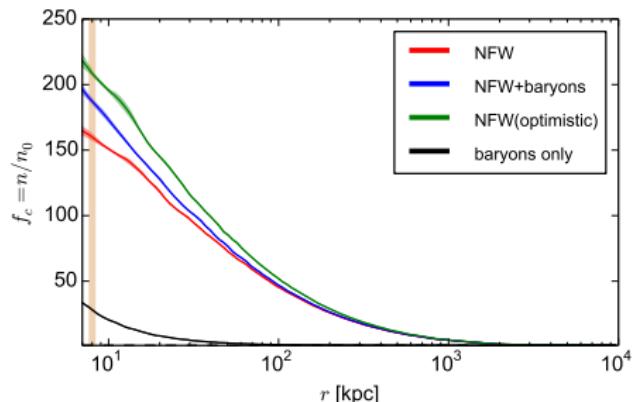
(from global fit [SG et al., 2017]:  $m_4 \simeq 1.3$  eV,  $|U_{e4}|^2 \simeq 0.02$ )

# Overdensity of a sterile neutrino

[arxiv:1706(6|7).[0-9]{5}]

$$\Gamma_4^{M(D)} \simeq \Delta N_{\text{eff}} |U_{e4}|^2 f_c(m_4) \Gamma_{C\nu B}^{M(D)}$$

$$m_4 \simeq 1.3 \text{ eV}, |U_{e4}|^2 \simeq 0.02$$



matter halo	overdensity $f_4$	$\Delta N_{\text{eff}}$	$\Gamma_{\text{tot}}^D (\text{yr}^{-1})$	$\Gamma_{\text{tot}}^M (\text{yr}^{-1})$
NFW(+bar)	159.9 (187.3)	0.2	2.6 (3.0)	5.2 (6.1)
		1.0	13.0 (15.2)	26.0 (30.4)
NFW optimistic	208.6	0.2	3.4	6.8
		1.0	16.9	33.9
EIN(+bar)	105.1 (139.5)	0.2	1.7 (2.3)	3.4 (4.5)
		1.0	8.5 (11.3)	17.1 (22.7)
EIN optimistic	203.5	0.2	3.3	6.6
		1.0	16.5	33.0